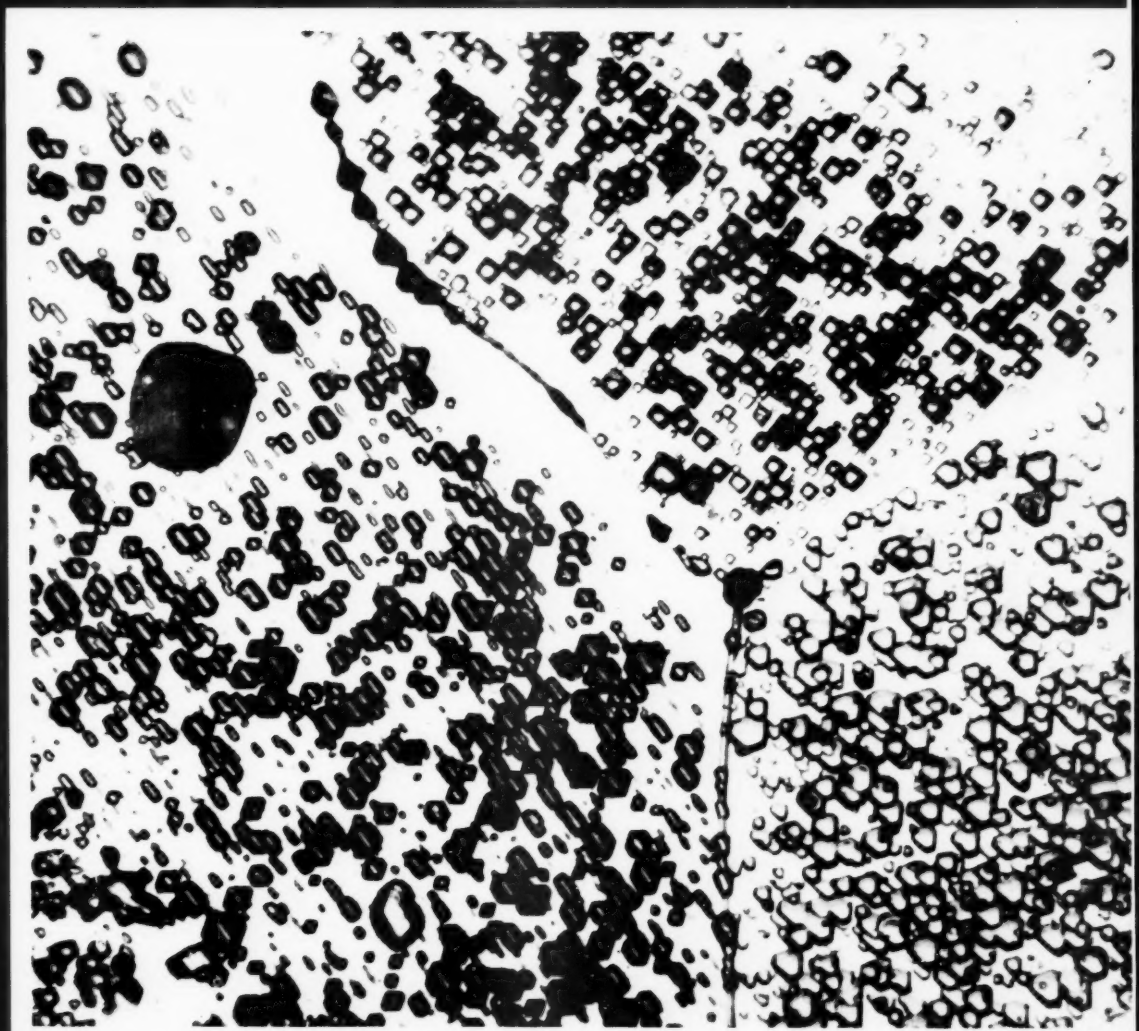
RAYTHEON

VOLUME 1 NO. 1

ELECTRONIC PROGRESS

JULY AUGUST 1956



ETCH PITS — Manganese — Magnesium Ferrite

In this issue: FERRITE MATERIALS

ELECTRONIC PROGRESS

VOLUME 1 **JULY - AUGUST 1956** **NUMBER 1**

RAYTHEON

ELECTRONIC PROGRESS

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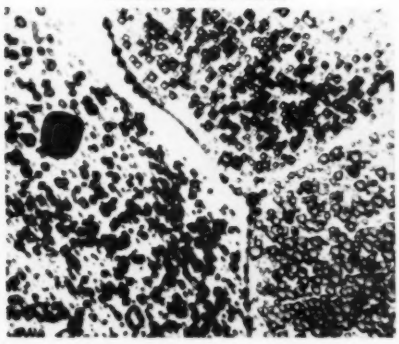
THE COVER



The cover picture is a polished and etched specimen of a manganese magnesium ferrite. This particular ferrite is the type used in memory devices. The very pronounced etch pits are evidenced in the grains and show the crystallographic orientation of the individual grains. This photograph is a bright field picture taken on a Bausch and Lomb metallograph.

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Calendar

Northeastern University Off-Campus Courses

	Place	*Time and Date*
Advanced Mathematics	**Publications Bldg.**	**September**
Theoretical Physics	**Waltham**	**date and time**
Physics of Semiconductors		**to be announced**
Microwave Tubes		
Radar Engineering		
Transistor Circuit Engineering		

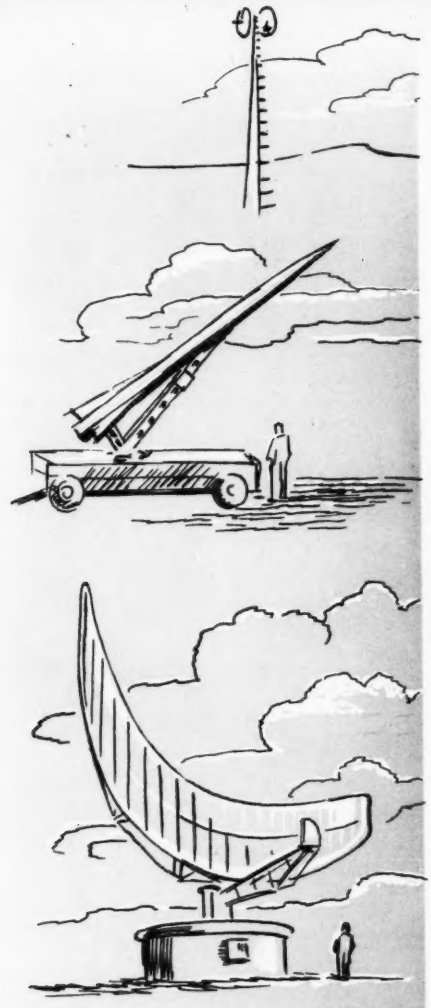
Other Seminars and Courses

Welding Engineering	**Brandeis Waltham**	**Tues. 6-8 p.m. June 19 until Aug. 28**

Technical Committee Meetings

	Place	*Time and Date*
Plastics	**Varies**	**2nd Tues. or Thurs. of the month**
Ferrite	**Varies**	**1st Wednesday of month at 3:00 p.m.**
Transistor Circuit	**Research**	**As required**
Welding	**Varies**	**No July meeting 1st Thursday of month at 3:00 p.m.**
Engineering and Scientific Co-ordinating Committee for		
Digital Computers	**Research**	**As required**
Space Charge	**Research**	**As required**
Ceramics	**Research**	**July 24 (tentative)**

Technical and engineering personnel who desire further information concerning the above calendar should contact Mr. James Sterling, Research Division, Waltham, X-2187.



Your new technical magazine

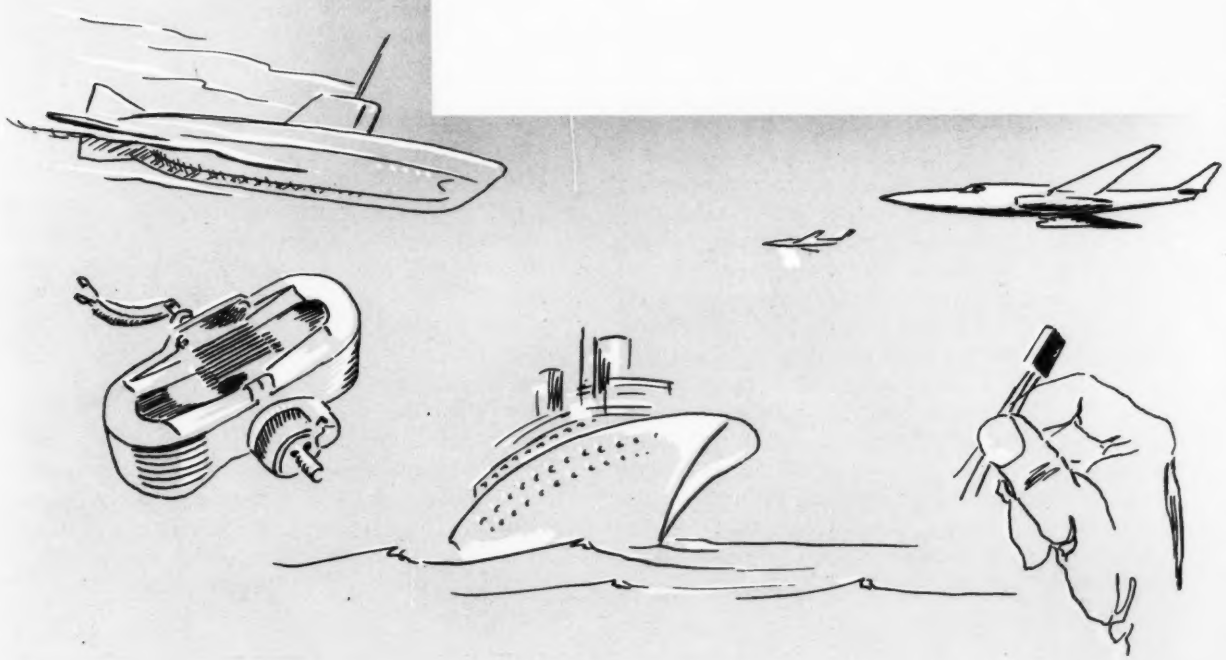
The technical personnel of Raytheon have long felt and voiced the need for bettering the interchange of technical information within the Company. Also, although the need is not so immediately pressing, there have been no media by which information concerning the technical activities of the Company could be disseminated to supervisory personnel in general for background and interest. The function of this publication is to help fulfill these needs.

Of the initial considerations, the most thought-provoking was how this goal could be attained in view of the scope of Raytheon's activities and the range of technical fields of specialization. The engineering staff of the Company numbers almost two thousand people whose jobs range from the frontiers of theory to the frontiers of practicality. Development, design, research, production, field service, and sales are broad classifications exampling this spread. Any one of these classifications may have personnel who have specialized in one of many scientific fields.

It cannot be the intent of this publication to present technical material in depth. Rather the emphasis must be on broader information which will inform and generate thought. One function should be to stimulate contact between technical groups.

Raytheon stands basically on its engineering achievements. These in turn depend on contributions of both technical and nontechnical groups. The latter in many instances want to know and need to know about the Company's general technical activities. It is hoped that while maintaining suitable technical perspective, "Electronic Progress" will prove valuable to people of this group as well as to the technical personnel of Raytheon.

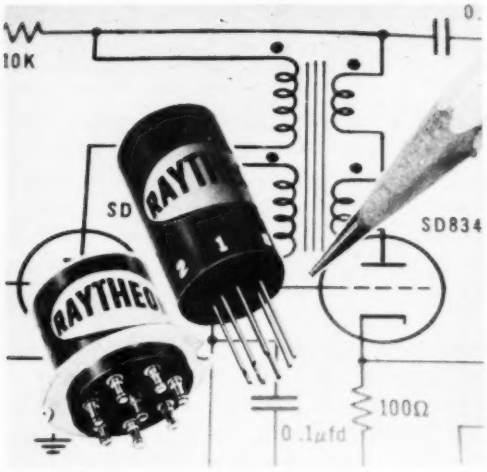
IVAN A. GETTING
Vice President, Engineering and Research



Ferrite Materials

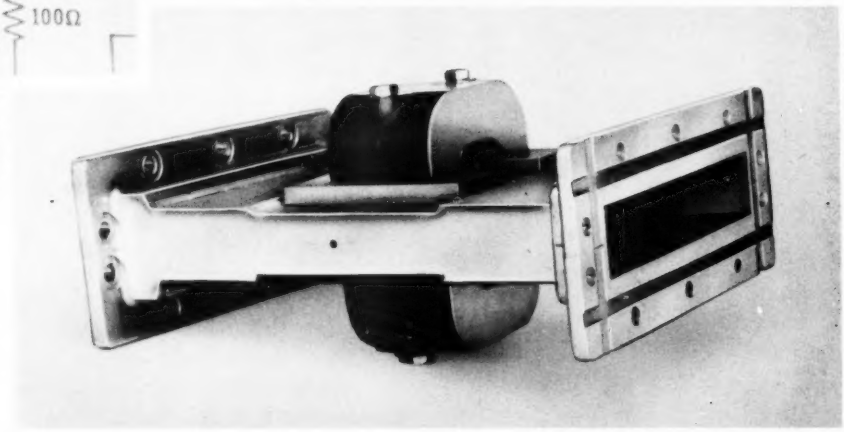
MARSHALL H. SIRVETZ

Research Staff Member,
Research Division



Computer pulse transformers, developed by Raytheon's Transformer Division, utilize ferrite cores for minimum size, high ratio of magnetizing inductance to leakage inductance.

L Band Ferrite Isolator under development by the Microwave Section of the Equipment Engineering Division. This isolator uses special material developed in the Research Division.



OF the new materials being applied in electronic equipment ferrites are among the most interesting. Their unique properties are useful, in general, in devices where high resistivity is of great importance while a somewhat low value of induction is not a great disadvantage. Thus, present applications are exampled by cores for radio frequency and fast switching and in microwave devices.

As might be expected, the requirements on material properties are different in the different applications. As core material for radio frequency devices, ferrites have significant advantages over the laminated or powder cores previously used and necessitated by the occurrence of eddy current losses. These advantages include the possibility of producing simply and economically the shapes commonly required, by well-known ceramic techniques. Of more importance, however, are the high permeability and Q at frequencies up to many megacycles. The ferrites used in this frequency region are nearly all nickel-zinc or manganese-zinc ferrites, sometimes containing small amounts of Cu, Co, or other additives for reasons probably connected with the sintering process. These materials represent variation in Curie temperature, T_c, from just above room temperature to about 600°C, in initial permeability from 10 to 5000, in μ max from 100 to 12,000. Of course, in any particular application, it is necessary to consider the range of frequencies involved, the permeability desired and the permissible losses, along with the sort of temperature stability required, and to choose the particular composition which most nearly meets these specifications.

The properties mentioned above are, in general, not independently variable through change in composition, and a qualitative description of the way they are interrelated may not be out of place here. Suppose that we start with nickel ferrite and successively replace nickel by increasing amounts of zinc. (See Fig. 1.) Then T_c decreases from 600°C to below room temperature, with corresponding increase in temperature coefficient of permeability. Magnetocrystalline anisotropy decreases in this series so μ_o at low frequency (about 10 kc) increases from a value of about 10 to values up to 500. (M_s has a maximum value near the middle of this composition range, and this distorts the course of the variation of μ_o with T_c somewhat.) Anisotropy has a further effect in that it is related to the frequency at which resonance losses occur. Since this frequency decreases with decreasing anisotropy, the

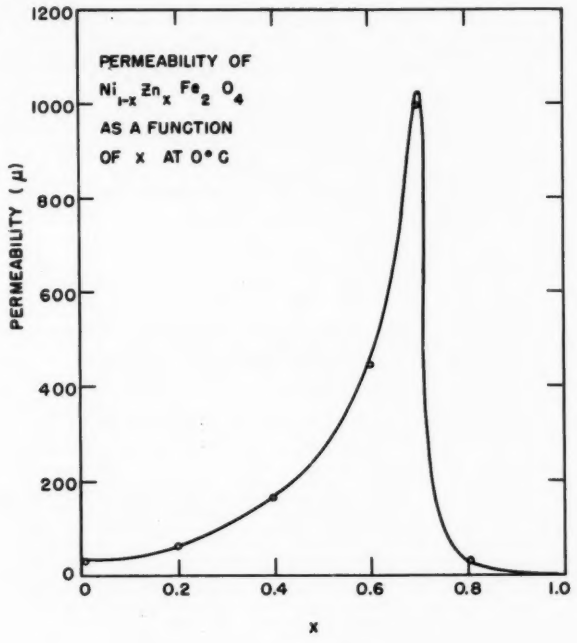


FIGURE I.

materials with high μ_o tend to have an associated Q which falls off at relatively low frequencies. Thus, whereas nickel ferrite is reported to have a practically constant, though relatively low, value of μQ up to 10 mc, the high zinc content materials show a sharp decrease in μQ below 1 mc.

The manganese-zinc ferrites show particularly low loss at frequencies below 1 mc. This is presumably associated with the very small value of magnetostriction of these materials, and makes them useful where high Q is required.

The materials discussed above constitute by far the major portion of the commercial output of ferrites at present. They are used in such economically important devices as flyback transformers and deflection yokes for television and antenna rods in radios. The high Q bodies are used in precision inductors for filter circuits. Probably every company producing ferrites for radio-frequency applications makes one or more bodies of this type.

Another prominent present day application of ferrites is their use in the memory matrix in high-speed computers. It has been found that in a certain region of the triaxial diagram, $MgO\text{-}MnO\text{-}Fe_2O_3$, the desired properties are obtainable. These properties are: switching time less than 1 μ sec; low coercive force; high value of Br/Bs ($\gtrsim$ 0.9); high squareness ratio, which means sufficiently slight response to one-half pulse (in two-dimensional memory) or two-third pulse (in three-dimensional memory) for unambiguous core selection. These properties apparently are connected with the ability of manganese to take on various valences as a function of firing temperature and atmosphere, as well as with the details of the ceramic structure, such as grain size. The properties of interest here are obviously in the hi[illegible]egree structure sensitive, and very careful con[illegible] the processing variables is required for cons[illegible]ut of cores of high quality.

It should be mentione[illegible]hat these materials have coercive force of about 1 oe. This is in a sense the price paid for the very fast switching time. Where the latter requirement is less stringent, as in magnetic amplifiers, it should be possible to produce materials of considerably smaller coercive force. Presumably at some frequency (greater than 60 cycles) where laminated cores show an eddy current contribution to coercive force, ferrite cores will have an advantage. This remains a matter for future development.

At microwave frequencies ferrites are used to produce phase shift or attenuation. Depending on the way the ferrite is placed in the wave-guide the effects may be reciprocal or nonreciprocal. Requirements on materials will usually be expressed in terms of maximum acceptable loss in a phase-shifter or maximum insertion loss in the forward direction for an attenuator. Part of the loss is describable as dielectric loss, due to finite conductivity of the material, and is not very frequency dependent. Other loss mechanisms are known which produce loss strongly dependent on frequency. The effect of these is, in general, to make any given ferrite useful only above a certain frequency. This lower frequency limit will, however, depend on the type of device.

Until recently, most interest was centered on x-band frequencies. In this region ferrites in the magnesium-manganese system have proved useful. The compositions which were chosen to give maximum rotation per unit loss have excess MgO which presumably gives the high resistivity. While the ferromagnetic resonance losses are comparatively broad, they do not have a large effect at the values of bias field used in phase-shift (or rotation) devices. Moreover, the loss in the partially magnetized condition, where rotation is roughly proportional to applied field, are small, so that devices requiring variable rotation are possible. In high power applications (for example, more than 200 watts average power) these small losses become important, it even being possible to heat the material above its Curie point at these power levels. It is usually assumed that details of ceramic preparation affect the loss considerably, and much effort of an empirical sort has gone into studies of these effects.

Nickel ferrite for x-band will give the advantage of high Curie point $T_c \approx 600°C$, compared to 250°C for MgMn ferrites.

No specific information is available on loss in this material, and it may be that increased loss tends to cancel the potential advantage that this material has in high power applications. Nickel ferrite has large loss in the partially magnetized state, and thus cannot be used very well in devices requiring rotation proportional to applied field.

No ferrite has been developed specifically for frequencies above x-band, but there seems no reason to believe that x-band ferrites will not be satisfactory in this region. Indeed the loss due to ferromagnetic resonance, which is believed to be of importance at x-band, will be decreased.

At frequencies below x-band the ferrites discussed above become lossy. At present, no manufacturer is producing a ferrite designed for one of the lower frequency bands, though results have been obtained in various laboratories which indicate the direction that development should take. Magnesium-aluminate ferrites should permit construction of isolators down to s-band, and presumably such materials will become available in the near future. These materials will have the disadvantage of low Curie points, possibly of the order of 150°C. Materials with narrow resonance absorption regions are under development in various laboratories. (See Figure 2.) Such materials will have normal Curie points and may be preferable in some applications, but their commercial availability is probably more remote.

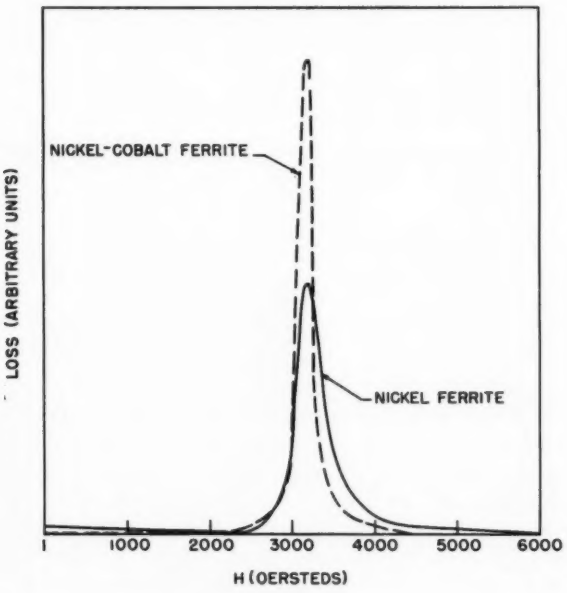


FIGURE 2.

The above curves show how minor additions of cobalt may be used to narrow the ferromagnetic resonance of nickel ferrite in order to extend its range of application to lower frequencies.

Still lower frequencies, down to 400 mc, are of interest at present. This is really a field of active research and little can be said. Extrapolations can be made from experience at higher frequencies, and these have led some investigators to claim that even with the furthest development of materials, there will be a lower frequency limit for devices of the isolator type at about 1000 mc.

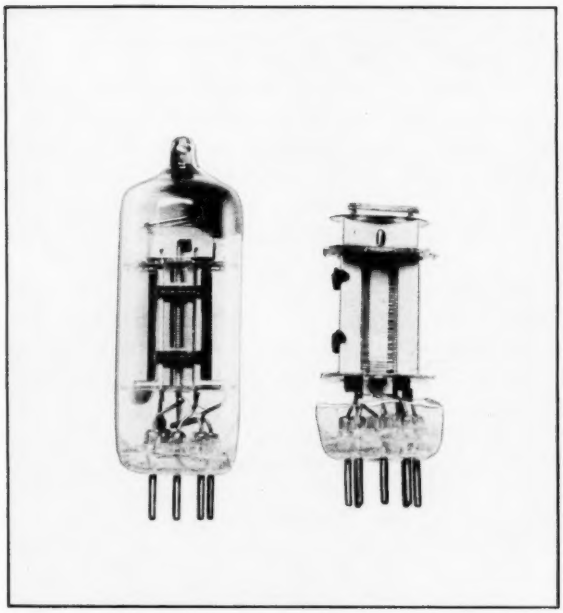
In addition, there are some miscellaneous applications of ferrites which bear mention. Among these are the permanent magnet materials and the magnetostrictive ferrites. In the first class only cobalt ferrite of the true (spinel) ferrites appears to hold promise. It has been found possible to produce an oriented material with high coercive force by making use of the large magnetocrystalline anisotropy, but no such material is available commercially. A material known as barium ferrite has good permanent magnet properties and, while different from the true ferrites in structure, it is prepared by similar techniques. It is a ceramic and has high resistivity. It can thus be used in wave-guide devices either alone or in conjunction with magnetically soft ferrites.

The magnetostrictive effect in ferrites can be used to produce electromechanical transducers, as well as sharply tuned circuit elements such as filters. In general, it seems that the electromechanical coupling coefficients are rather small and tend to limit their use as transducers to low power applications. In the form of filters and frequency stabilizing elements, ferrites have some utility. The material constants are such that elements (toroids or rods) of size of the order of 1 cm. have a mechanical resonance at frequencies in the 100 kc range. No ferrite is known to us to have been developed specifically for this purpose. The widely available nickel and nickel-zinc ferrites appear to be satisfactory for many applications. Coupling coefficients are of the order .01 to .1; temperature coefficients of resonant frequency are of the order of 10×10^{-6}. The mechanical Q of these materials tends to be high, in the range 1000 to 5000; there is, furthermore, some evidence that Q is sensitive to presence of impurities.

Reliability in Computer Tubes

EDMUND S. MOCKUS

Development Engineer,
Special Tube Division,
Receiving & Cathode Ray Tube Operations



6AN5 Pentode, manufactured by the Receiving and Cathode Ray Tube Operations.

COMPUTERS are operated under conditions that demand special purpose tubes which must not only meet special electrical requirements but must also have a high degree of reliability. This paper will deal with computer tube reliability and specific references will be made to the 6AN5 and 6AN5WA which were developed for computer use. Tube reliability has different meanings depending largely upon the tube application. For computers, a definition of tube reliability may be stated as follows: for several thousands of hours under all types of drain conditions, including cut-off operation, there should be (1) freedom from interface resistance, (2) a minimum deterioration of electrical characteristics, and (3) a minimum of catastrophic failures such as shorts, opens, and gassy tubes.

In designing computer tubes one of the most important factors is to prevent the formation of interface impedance which can build up rapidly on cut-off life. This interface compound is usually barium orthosilicate. In order to minimize the rate of formation of this compound, it is necessary to use a nickel alloy for the cathode sleeve having as low a silicon content as possible. The importance of such a step is evident from Table 1, which gives the average interface resistance results obtained on the 6AN5 with different nickel alloys.

Another, but appreciably lesser, source of silicon is the cathode tab. The results in Table 2 show the need of using a low silicon content nickel alloy for the tab.

TABLE 1

Effect of Nickel Alloy on Interface Resistance for Tubes Operated Cut-Off for 3500 Hours

Alloy	% Silicon	Average Interface Resistance
499 (control)	.01 maximum	0 ohms
A31	.02 nominal	35 ohms
225	.2 nominal	170 ohms

TABLE 2

Effect of Tab Material on Interface Resistance for Tubes Operated Cut-Off for 2800 Hours with 7.5 Volts on the Heaters

Tab Material	% Silicon	Average Interface Resistance
Grade A nickel	.1 nominal	80 ohms
Silicon nickel	4.0 nominal	166 ohms

It should be stressed, relative to the results in Table 2, that at normal heater voltages the 6AN5 will not develop a measurable interface resistance even under cut-off conditions for several thousands of hours. However, interface resistance formation can be highly accelerated by high heater voltages (i.e., high cathode temperatures) and this technique was necessary in order to evaluate design changes on the 6AN5. Some preliminary work indicates that at 7.5 volts on the heater the rate of interface resistance formation is more than ten times as fast as with 6.3 volts on the heater.

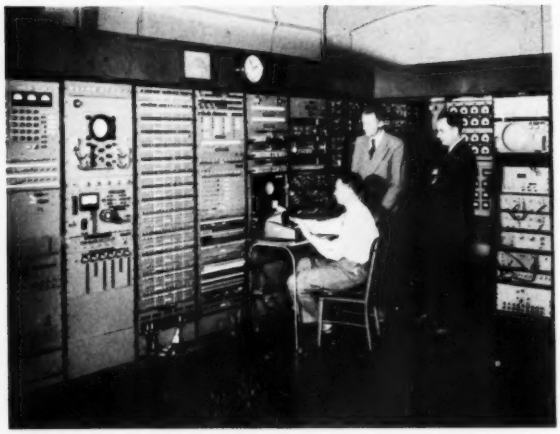


Photo — Courtesy M. I. T.

The operation center for Whirlwind I, the high-speed electronic computer at M.I.T. With a built-in "memory" and the ability to act upon and deliver information at a rate of 20,000 times a second, Whirlwind is the first machine suitable for supplying instantaneous instructions for such applications as controlling aircraft traffic patterns.

Tube engineers have felt for a long time that there are several possible modifications in tube design and manufacturing techniques which would prove to be effective in making special purpose tubes with long life and freedom from catastrophic failures. Some of these modifications which were embodied in the 6AN5 consisted of (1) thorough out-gassing of parts at pre-processing and at exhaust, (2) slow schedules for cathode activation, (3) special attention to the control and removal of lint, and (4) the use of statistical quality control coupled with tight acceptance limits in the different phases of tube parts fabrication and final assembly. Taken individually the effect of the various factors is difficult to analyze, but taken together the overall effect of these changes can be approximated from the field results obtained on the 6AN5.

In the National Bureau of Standards SEAC Computer 1,050 of the tube sockets were filled with the 6AN5 and extensive reliability testing of this tube was performed as part of the computer program. All tubes were removed every three months from the computer and were re-tested as a preventative maintenance measure. One of the criteria for tube rejection at these tests was a 25% drop in plate current for a 10% drop in heater voltage. It was felt that such a test might pick out imminent electrical characteristics failures. Later engineering studies established that this was not a reliable indicator of future tube performance. In spite of the fact that a majority of 6AN5 tubes were taken out of the computer as rejects because of that arbitrary criterion, a median life of 13,000 hours was obtained on a lot of 346 6AN5s used in one of the computer sections. The median life of all 6AN5 tubes used in the computer (numbering 1,775) was 8,700 hours; this lower median life was due in part to the inclusion of data on tubes which were inadvertently operated at excessively high heater voltages. Under more normal conditions of both operation and in-life testing the 6AN5 can be expected to yield better than the reported life figures. No interface resistance was found (using a pulse overshoot technique for evaluation) on samples of rejects from different stages of life. In service failures (i.e., catastrophic) all the 6AN5 tubes averaged out to 1.3% per year.

At the M.I.T. Project Whirlwind Laboratories 6AN5 tubes were operated under drain conditions simulating those encountered in the Whirlwind Computer. Regular drain conditions consisted of 120 volts D.C. on the plate and screen grid with bias on the control grid from a 125 ohm cathode resistor. In the flip-flop condition an approximate duty cycle of 50% was established. The cut-off condition was attained with a negative potential of 15 volts on the control grid and with all other elements left floating. The average results are given in Table 3.

TABLE 3

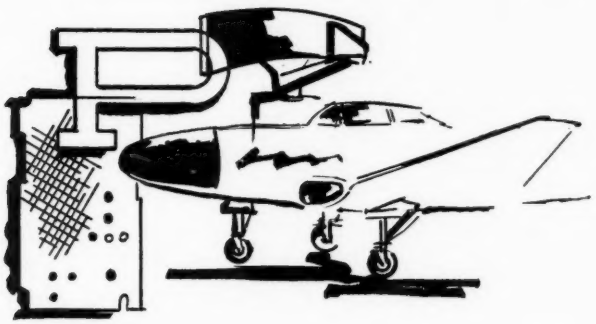
6AN5 Plate Current Decay After 8000 Hours of Life

Drain Condition	% Change in Ibs from Zero to 8000 Hours of Life
Regular	3% drop
Cut-off	5% drop
Flip-Flop	9% drop

The worst case after 8000 hours of life (just under a year!) was the flip-flop where an average plate current decay of 9% was recorded. This is in sharp contrast to regular receiving tubes where a 9% change in plate current oftentimes occurs in less than 500 hours (3 weeks) of life even under more optimum drain conditions.

The experience gained with the 6AN5 has helped in the development of a ruggedized version (6AN-5WA) for military and other critical applications. This new tube must pass tighter specifications for vibration, heater-cathode leakage, noise, and many other parameters. Also there are tests on new items such as shock, fatigue, glass strain, heater cycling, high altitude high voltage breakdown, and other reliability and ruggedness factors.

Some Notes on Plastics at Raytheon



R. L. MONDANO

Research Staff Member, Research Division

IN the past five years Raytheon has seen a large influx of new basic engineering materials, a large number of which fall into the general category of plastics. Many applications of these organic materials have already been made and as more of their properties become known more and varied applications can be expected.

To keep abreast of this quick moving industry, Raytheon has established a Plastics Committee to follow new developments and to aid in the interchange of information and techniques between various Raytheon groups which have applications for plastics. This Committee meets monthly to discuss and act on information concerning plastic problems, materials, and techniques. At the suggestion of Dr. I. A. Getting in 1953, this Committee coordinated the preparation and issuance of a Plastics Handbook which is being kept up to date.

Recently some very startling and valuable plastic materials and techniques have become available. New low density silicone foams of approximately three to four pounds per cubic foot, as well as 100 per cent solids silicone casting resins stimulate the imagination for possible fruitful application. Continual development in the field of high temperature resins gives promise in the near future of resins suitable for continual operation at 600° F. Penton, a chlorinated polyether, is a new injection molding plastic with good electrical properties. It has found its niche on the list of plastics for electronics. Liquid casting resins have been developed that can be suitably controlled and handled by the engineer. The technique of positioning several electronic components in a mold and casting a liquid resin in position to freeze these components relative to each other is a technique the possibilities of which have scarcely been scratched.

Raytheon is presently using some of just about all of the general types of plastics manufactured. This involves compression molded, injection molded, vacuum and mechanically formed and calendered as well as transfer molded manufacturing processes. The Company's present activity in plastics includes such projects as radome materials development, radome fabrication techniques, small high-tolerance plastic radomes, and several special adhesive problems which fall in the general category of plastics. In addition, important work has been done on radar reflectors where the strength and weight characteristics of plastic materials and forms have been used in several different designs. Within Raytheon a sodium ammonia process for preparing Teflon surfaces for bonding is being set up. This process now makes it possible to get good bonds of Teflon to any other bondable surfaces.

In a succeeding issue of this publication it is the intent to discuss plastic materials, applications and techniques more broadly as they concern Raytheon.

Inventions

Congratulations to the following persons for their valuable contributions to Raytheon's portfolio of inventions:

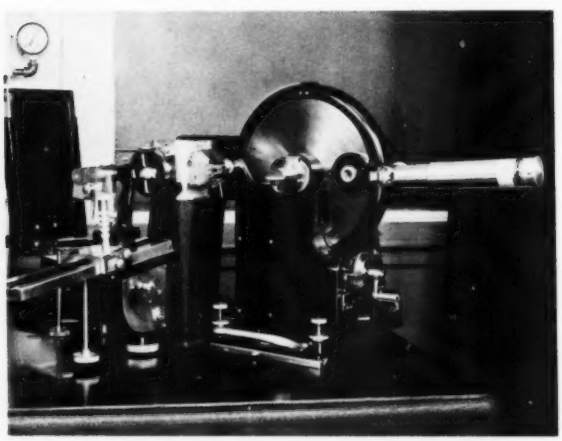
Name	*Field of Invention*
Leo J. Cronin	Getter
Duane B. Haagensen	Electronic Heating Apparatus
Norman B. Saunders	Frequency Responsive Systems
Marshall H. Sirvetz	Ferrite Composition

Raytheon Facilities

X-Ray Diffractometer and Electron Microscope

THE Techniques Department of the Microwave and Power Tube Operations was established to provide support for the microwave tube development programs of Raytheon. Because of its specialized personnel and equipment many other areas of Raytheon have availed themselves of help from this group. In particular, the laboratory is especially well-equipped to investigate the physical structure of materials. For this work two Norelco X-ray equipments with various accessories, and an R.C.A. type EML-1A Electron Microscope are used.

X-ray diffraction studies can be made with the Geiger Counter X-ray Diffractometer which combines a basic X-ray diffraction unit with a strip chart recorder. Various other accessories such as a high angle goniometer, a parallel beam monochrometer using a germanium single crystal and a double crystal spectrometer are available to extend the usefulness of the basic equipments. High temperature X-ray studies in controlled atmospheres as well as vacuum can be carried out by means of a special camera of Raytheon design.



This x-ray diffractometer is used to identify phases in ceramic oxides. Other uses include strain analysis, quality control of raw materials, and determination of grain size.

ELECTRON MICROSCOPE permits magnification as high as 200,000 diameters — many times that of the best optical devices.

The electron microscope permits magnifications up to 200,000 diameters; considerably greater than the approximate 2000 diameter theoretical limit for optical microscopes. The low penetrating power of the electron beam makes it necessary to use thin plastic replicas of the surface under study. The magnified image of this replica is then displayed on a fluorescent screen. Electron diffraction patterns can also be obtained with this equipment.

Both the X-ray and electron microscope equipments are used primarily in physical metallurgy problems although their use is by no means restricted to this area. The low penetrating power of the electron beam makes the electron microscope most useful for the study of surfaces. However, its characteristics also make it well-suited to the study of smaller crystallites or thinner films of material than possible with X-ray equipment. On the other hand X-ray techniques are used to explore the deeper structures of materials.

Typical studies being made with the X-ray units are the measurement of various lattice parameters, identification of various materials, study of thoria concentration gradients, study of ordering of germanium-silicon alloys, and orientation of single crystal germanium.

The electron microscope has proven most useful in surface structure studies. Some of the areas of greatest use to date are the studies of size, shape, and distribution of powders in cermets, ceramics and ferrites, studies of surface preparation of cathodes, studies of microstructure of fine grained alloys at ceramic-to-metal seal interfaces and studies correlating the substructure in cermets, ferrites and semi-conductors with their emitting, magnetic and electrical characteristics.

A bibliography of applications both in Raytheon and in other industries is available from Mr. L. J. Cronin, who is head of the Techniques Department.

Publications & Papers

"A Note on Forced Convection Tube Cooling with Chimneys"

MELVIN MARK

National Conference on Aeronautical Electronics,
Dayton, Ohio, May 1956

Abstract: A vacuum tube envelope temperature is generally maintained below some predetermined level to obtain the desired life and performance from the tube. To accomplish this, a hollow cylinder or chimney can be placed over the tube and air forced through the annulus between cylinder and tube. By properly selecting the air flow and the inner diameter of the chimney with respect to the tube diameter, the heat transfer coefficient from the tube surface can be controlled to give a desired tube envelope temperature.

"Life Test Performance of Reliable Tubes at Maximum Ratings"

T. J. WHITE

National Conference on Aeronautical Electronics,
Dayton, Ohio, May 1956

Abstract: The results of a recent investigation made by Raytheon, under Bureau of Ships sponsorship, add definite quantitative information to the presently nebulous definitions that exist regarding absolute maximum tube ratings. In general, the definition of "absolute maximum" is a rating beyond which tube performance may be impaired. This paper will attempt to clarify the question that logically arises from this type definition — "how much is performance impaired when tubes are operated at or near their maximum ratings?"

"Structure of Surface States on Silicon from Conductance Measurements of N-Type Inversion Layers"

G. de MARS, H. STATZ, L. DAVIS, JR., and A. ADAMS, JR.

American Physical Society Meeting, Pittsburgh, Pa., March 15, 1956, through March 17, 1956, by H. Statz

Abstract: N-type inversion layers on p-type silicon are observed when an etched surface is exposed to dry ammonia. Measurements of the steadystate conductance of the inversion layer as a function of bias voltage have been made on bars with a transistor like n-p-n structure. The measurements can be interpreted by assuming a large total density of states. By careful analysis it is possible to determine an upper limit of the thickness of the oxide film. Depending on the degree of oxidation, thickness of the order of 10Å or more have been obtained. Detailed results will be presented.

"Grain Growth in Ferrites"

L. GERLACH and P. LEVESQUE

American Ceramics Society Meeting, April, 1956

Abstract: Continuous and discontinuous grain growth in nickel ferrites is discussed. Experimental evidence is presented which indicates that excess iron oxide is responsible for the exaggerated grain growth. Photomicrographs are given.

"Status Report on Semiconductor Surfaces" Technical Report R-7, October, 1955

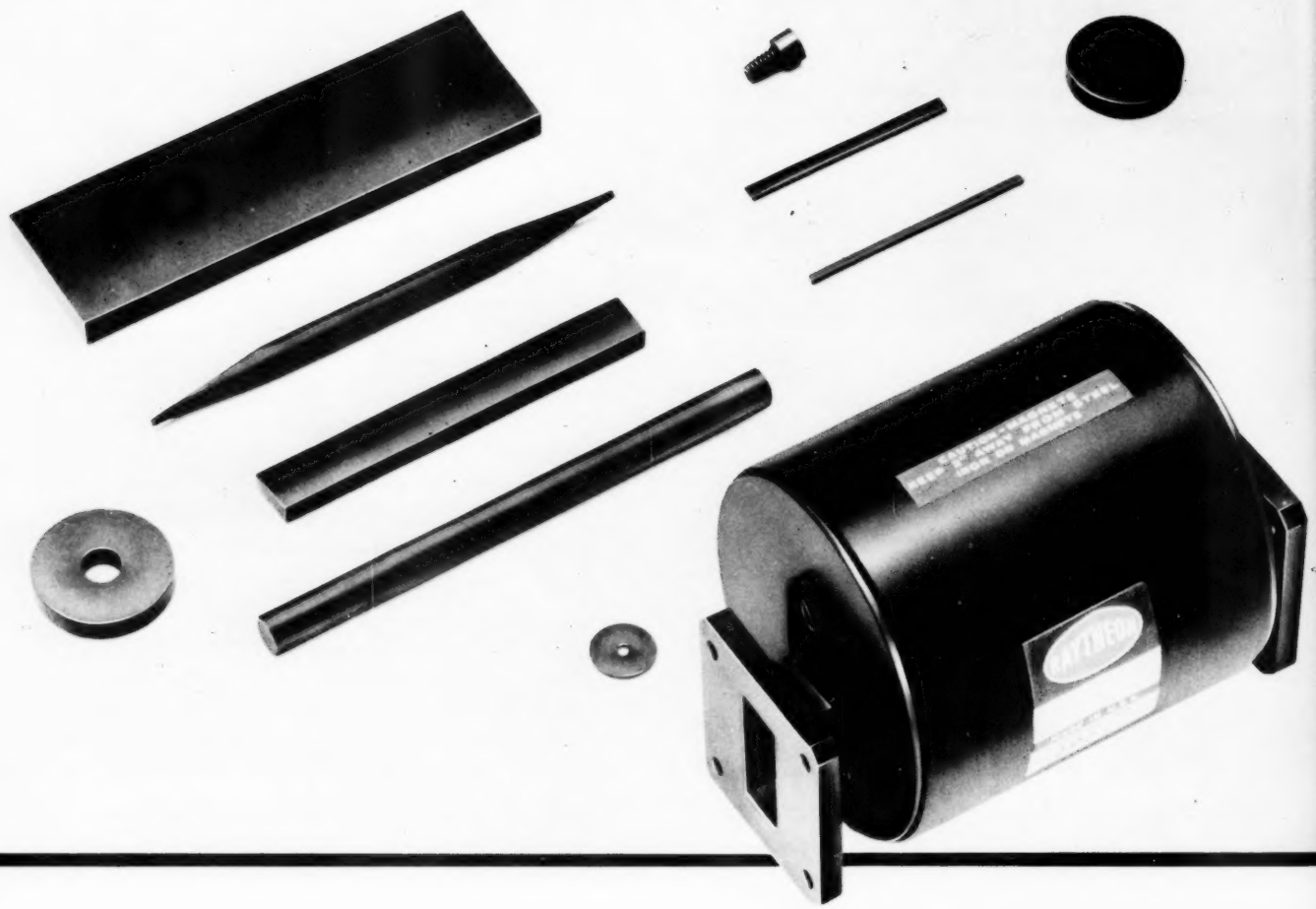
H. STATZ, G. de MARS, and W. ERIKSEN

Abstract: Measurements and interpretation of p-type inversion layer conductance on n-type germanium are reported. The experiments can be understood in terms of a very large density of surface states on the germanium oxide surface and a smaller density of states at the germanium germanium-oxide interface. The former states are believed to result from adsorbed oxygen; the latter states are found to have a sharp energy level at 0.138 ev below the middle of the gap, and are believed to result from some imperfection. The theory of water-induced conduction across p-n junctions is reviewed. As yet no definite mechanism for this conduction can be given.

"Delay Time of Plastic Flow in Germanium"

JAMES PATEL

The time delay of plastic flow in germanium has been shown to follow the relationship $\tau = \tau_0 \exp\left(\frac{Q}{RT}\right)$, where τ is the delay time and Q the activation energy for freeing locked Frank-Read generators. Experimentally τ_0, the limiting time for plastic flow in very pure materials, was found to be 10^{-9} sec. and agrees very closely with Seitz's theoretical prediction. The value of the activation energy Q was 39,000 cal/mol. Since this value agrees closely with Esaki's determination for the diffusion of copper in germanium below 600°C, it is possible that the impurity locking the Frank-Read generators is copper.



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